PERFORMANCE REPORT

A Biologically-Inspired Autonomous Robot

Grant N00014-90-J-1545

Period of Performance: 3 Years

Starting Date: January 1, 1993

December 13, 1993

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Research Progress

- A treadmill has been developed to support our cockroach locomotion studies. We have developed a small treadmill with a transparent belt for studying leg joint movements along with EMGs as the animal walks or runs at various speeds. This allows us to match the electrical activity in muscles with the kinematics of joint movement. Along with intracellular stimulation studies performed previously, we now have the tools in place to make major advances in understanding how the insect's walking movements are actually accomplished.

- We have begun to address the question of how the cockroach increases its speed of walking (Watson and Ritzmann, 1993). Some possibilities are: (a) make larger joint movements; (b) move through the same joint angles at a higher speed; or (c) spend less time in transition between flexion and extension. Our preliminary data suggest that (a) does not happen but both (b) and (c) do. Moreover, the animal moves faster by first increasing the firing rate and facilitation of slow motor neurons, then, when this is no longer sufficient, fast motor neurons are activated. An individual action potential in a fast motor neuron can cause a very rapid and large leg movement.

- We have begun to quantify the forces that are developed when specific motor neurons are activated. This will be crucial to a detailed understanding of the relationship between motor neuron activity and leg movement. Currently, we are activating motor neurons extracellularly by stimulating small nerve bundles. Eventually, we will use intracellular stimulation to get even more specific readings.

- As part of our efforts to construct a biologically realistic computer model of cockroach walking, we have undertaken a detailed biomechanical analysis of the femur-tibia joint of the metathoracic leg of the cockroach (Marx, Beer, Nelson, et. al., 1993). We are focusing on this joint first because it provides one of the simpler neuromuscular structures found in cockroach legs. By analyzing digitized movement data of slow walks and combining these observations with other experimental measurements (segment inertias, leg geometry and passive length-tension curves of the flexor and extensor muscles), we have been able to demonstrate the following: (1) Passive damping effects and passive muscle tension due to stretch dominate inertial and gravitational torques during swing phase; (2) The femur-tibia joint is approximately 3.4 times overdamped; (3) The early portion of swing phase in this joint (which is a very high acceleration and high velocity movement) is due almost entirely to the passive stretch properties of the flexor muscle after the extensor activity has ceased rather than

requiring any activation by the nervous system. As the flexor nears its rest length in the middle of swing phase, neural activation of this muscle completes the movement. By eliminating all of the passive effects described above, we have also been able to make a rough estimate of the torque generated by the electrical activation of the muscle dunng the movement.

- The previous simulation of the robot has been extended to include models of the motors and transmissions (Espenschied and Quinn, in press). Numerical results with this simulation exhibit general body motion and performance consistent with our initial experimental measurements. Interestingly, the simulation also predicts a pattern of ground reaction forces for the robot that shares features with Full's force measurements of cockroach walking.

- The 18 motor driver circuits for the robot have been completed and debugged, and they have been successfully interfaced to the robot and control computer.

AASERT Student

Bill Marx completed two courses this semester, Advanced Dynamics II and Functional Anatomy, as well as making significant progress on his thesis work (see description of cockroach leg model above).

Publications

Beer, R.D. (in press). A dynamical systems perspective on agent-environment interaction. To appear in *Artificial Intelligence*.

Beer, R.D. (in press). Computational and dynamical languages for autonomous agents. To appear in T. van Gelder and R. Port (Eds.), *Mind as Motion*. MIT Press.

Beer, R.D. (1993). Editorial. *Adaptive Behavior* **2**(1):1-3.

Chiel, H.J. and Beer, R.D. (1993). Neural and peripheral dynamics as determinants of patterned motor behavior. In D. Gardner (Ed.), *The Neurobiology of Neural Networks* (pp. 137-164). MIT Press.

Espenschied, K.S. and Quinn, R.D. (in press). Biologically-inspired hexapod design and simulation. To appear in the Proceedings of the AIAA Conference on Intelligent Robots in Field, Factory, Service and Space, Houston, Texas, March 20-24, 1994.

Marx, W.J., Beer, R.D., Nelson, G.M., Quinn, R.D. and Crocker, G.A. (1993). A biomechanical model of the cockroach leg. *Soc. of Neurosci.* **19**:1601.

Watson, J.T. and Ritzmann, R.E. (1993). Analysis of leg movements evoked by intracellular stimulation of neurons in the cockroach. *Soc. of Neurosci.* **19**:1601.

Submitted

Yamauchi, B. and Beer, R.D. Sequential behavior and learning in evolved dynamical neural networks. Submitted to *Adaptive Behavior.*

Presentations

R. Beer was an invited participant in the symposium on "Insects as Models in Behavioral Neuroscience," held at the National Meeting of the Entomological Society of America, Indianapolis, IN, December 12-16, 1993. He gave a talk entitled "Model Insects in Behavior al Neuroscience and Robotics."

R. Beer was an invited participant in the symposium on "Ecological Psychology and the New Artificial Intelligence: Seeking Common Ground," at the Seventh International Conference on Event Perception and Action, University of British Columbia, Vancouver, Canada, August 8-13, 1993. He gave a talk entitled "Adaptive Behavior in Natural and Artificial Agents."

R. Beer gave an invited talk entitled "Adaptive Behavior in Natural and Artificial Agents" at Oberlin College, Oberlin, OH, Oct. 28, 1993.

H. Chiel gave an invited talk entitled "Analysis and Synthesis of Adaptive Behavior" at the University of Chicago, Chicago, Illinois, Oct. 19, 1993.

H. Chiel gave an invited talk entitled "Analysis and Synthesis of Adaptive Behavior in Simpler Animals" at Hebrew University, Jerusalem, Israel, June 20, 1993.

K. Espenschied gave an invited talk entitled "Biologically-Inspired Mechanical Hexapod Control" at the GSRP Annual Symposium, NASA Goddard Space Flight Center, Greenbelt, Maryland, Sept. 15-17, 1993.

R. Quinn gave an invited talk entitled "Dynamics and Simulation of an Insect-Like Walking Robot" at the European Mechanics Colloquim 307 on Walking Machines, University of Duisburg, Duisberg, Germany, Sept. 8-10, 1993.

R. Quinn gave an invited talk entitled "Biologically-Inspired Neural Control of a Mechanical Hexapod" at the Workshop on Neural Networks, Ohio Aerospace Institute, Cleveland, OH, June 14-15, 1993.

R. Ritzmann gave an invited talk entitled "Control of Orientation and Locomotion Movements in an Insect" at Calvin College, Grand Rapids, Michigan on Oct. 3, 1993.